MISSION AND SIZING ANALYSIS FOR THE BETA II TWO-STAGE-TO-ORBIT VEHICLE

Shari-Beth Nadell*
William J. Baumgarten*
Stephen W. Alexander**
NASA Lewis Research Center, Cleveland, Ohio 44135

Abstract

NASA Lewis Research Center studied a horizontal takeoff and landing, fully reusable, two-stage-to-orbit (TSTO) vehicle capable of launching and returning a 10,000 lb payload to low Earth polar orbit using low-risk technology. The vehicle, called Beta II, was derived from the USAF/Boeing Beta vehicle, a TSTO study vehicle capable of launching a 50,000 lb payload to low Earth polar orbit. Development of Beta II from the USAF/Boeing Beta vehicle occurred in a series of iterations during which the size of the vehicle was decreased to accommodate the smaller payload, the staging Mach number was decreased from 8.0 to 6.5, and the rocket propulsion system was removed from the booster. The final Beta II vehicle consisted of a rocket powered orbiter and an all airbreathing booster. The gross takeoff weight of the Beta II vehicle was approximately 1.1 Mlb. In addition to its baseline mission, the Beta II vehicle was capable of delivering approximately 17,500 lb to the Space Station with the same takeoff gross weight. The mission and sizing analysis performed to arrive at the Beta II vehicle is discussed.

Introduction

Recently, much emphasis has been placed on developing a viable single-stage-to-orbit (SSTO) vehicle to transfer payloads to orbit. One such vehicle is the National Aerospace Plane (NASP). An alternate concept to SSTO is the two-stage-to-orbit vehicle. Technology development for TSTO vehicles does not involve as great a risk as that for SSTO vehicles. TSTO vehicle concepts are, therefore, potentially more viable using current or near-term technology than SSTO concepts.

NASA Lewis Research Center initiated a study to investigate a near-term (i.e., developed using 1995 technology) vehicle for delivering payloads to orbit. A TSTO concept was selected over SSTO based on the chosen technology level. The study guidelines mandated horizontal takeoff and landing and that both the booster and orbiter be fully reusable. The TSTO vehicle would be developed to deliver and return a 10,000 lb payload to low Earth polar orbit (100 n. mi.). This payload capability would capture a large part of projected NASA payload requirements. A survey of past TSTO studies revealed the Beta vehicle (Figure 1), developed by the U.S. Air Force (USAF) at Wright Laboratory and Boeing Aerospace and Electronics (ref. 1), as having incorporated guidelines and technology limits similar to those of the NASA study. The Beta study vehicle was therefore chosen as the starting point for the development of the NASA Lewis TSTO baseline vehicle, called Beta II.

The main goal of the study was to develop the Beta II vehicle to perform the design mission with a reasonable minimum takeoff gross weight. A reasonable minimum weight was defined as that which would enable operation from a conventional runway. A takeoff gross weight of approximately 1 Mlb, similar to a large commercial transport, was judged to satisfy this requirement. In addition, the possibility of performing the boost phase using an all airbreathing propulsion system in place of the combined airbreathing and rocket propulsion found on the USAF/Boeing Beta vehicle would be investigated. It was believed that this modification would decrease the gross weight of the vehicle and simplify ground handling operations. Development of Beta II from the USAF/Boeing Beta vehicle by the NASA Lewis TSTO team was supplemented by the U.S. Air Force at Wright Laboratory and the Boeing Defense and Space Group (refs. 1, 2). The mission and sizing analysis performed in-house at NASA Lewis Research Center to arrive at the Beta II vehicle and the methods used are discussed below.

* Aerospace Engineer, Member AIAA

** Aerospace Engineer

Beta II Development

Development of Beta II from the USAF/Boeing Beta study vehicle occurred in a series of iterations during which several modifications were made. The process followed during the Beta II development, along with important intermediate results, is depicted in Figure 2 and described below.

The initial configuration for the NASA Lewis TSTO study was the USAF/Boeing Beta vehicle shown in Figure 1. The USAF/Boeing Beta study vehicle featured a lifting body orbiter embedded into the underside of the booster stage. The lifting body orbiter provided large cross-range capability, while the embedded configuration offered expedient mating and staging procedures. The Beta vehicle was developed to deliver a 50,000 lb payload into low Earth polar orbit with a gross weight at takeoff of approximately 2 Mlb. Included in the gross weight of each vehicle stage was a small growth margin equal to 2 percent of the orbiter dry weight and 2.5 percent of the booster dry weight (ref. 1). This added weight accounts for the difference which inevitably appears between the predicted weight of a vehicle and its actual weight due to misinterpreted technology trends, manufacturing limits, etc.

Beta booster propulsion consisted of two ramjets, eight Advanced Tactical Fighter (ATF) turbofans, and one Space Shuttle Main Engine (SSME). One SSME modified with a two-position nozzle for improved performance powered the orbiter. The orbiter rocket, booster rocket, and booster airbreathing propulsion system provided thrust during the initial ascent. The main function of the ATF turbofans, however, was to provide power for transporting the orbiter between launch sites. Therefore, the contribution of the ATF turbofans to the initial ascent of the USAF/Boeing Beta vehicle was minimal. Propellant, both liquid oxygen (LOX) and liquid hydrogen (LH2), would be transferred from the booster to the orbiter during ascent to ensure that the orbiter tanks were full at separation. The Beta vehicle staged at Mach 8.0 and 100,000 ft. After separation the booster, powered by the turbofans, would return to the airfield; the orbiter SSME would provide the remaining impulse required to obtain orbit. Upon completion of the mission, the orbiter would return to Earth for a non-powered, shuttle-like, landing.

As indicated on Figure 2, the NASA Lewis TSTO development effort began by performing two sets of initial trade studies, one with the orbiter stage and one with the booster, to determine some of the basic vehicle characteristics that would be used throughout the study. These initial studies were performed with a TSTO vehicle based on the USAF/ Boeing configuration but scaled parametrically to produce results for the particular trade under investigation. The propulsion (including SSME performance) and aerodynamic data developed by the U.S. Air Force and Boeing for the Beta study vehicle were employed for these studies (ref. 1). The first trade study involved determining the initial orbiter thrust-to-weight ratio (T/W), i.e., the T/W occurring at orbiter rocket ignition, that would produce a minimum gross weight. Designing the orbiter at this initial, or staging, thrust-to-weight would further the goal of developing a vehicle with a minimum takeoff gross weight. The thrust and weight of the rocket engine used for this trade study were scaled such that the rocket was operating at a maximum thrust level at ignition. This thrust level was held constant throughout the trajectory. The second set of trade studies included investigating the possibility of removing the rocket propulsion system from the booster stage. If feasible, this modification could result in decreased vehicle gross weight and simplified ground handling operations. The combination of airbreathing propulsion systems (turbofan/ramjet) on the booster which would enable the vehicle to perform the initial ascent without rocket assist was then determined. Additional trade studies included varying the staging Mach number of the vehicle and decreasing the orbiter payload to meet NASA Lewis study guidelines.

Upon completion of the initial trade studies, the decision was made to study two TSTO vehicles derived from the USAF/Boeing Beta vehicle but incorporating the NASA Lewis payload and mission guidelines. In addition, the initial staging Mach number of 8.0, thought to be optimistic for a low-risk airbreathing propulsion system, was decreased. A staging Mach number of 6.5 was chosen for the first vehicle, referred to as Beta-B1. Prior experience at NASA Lewis suggested that Mach 6.5 was the operational limit of hydrogen fueled ramjets using 1995 technology. The second vehicle, Beta-B2, would be designed to stage at Mach 4.5. In addition, the ramjets on the Beta-B2 vehicle would be fueled with hydrocarbon fuel (JP-7) instead of hydrogen. Prior experience again suggested that Mach 4.5 was the operational limit of the ramjets when utilizing non-cryogenic hydrocarbon fuel. Both vehicles would perform the initial ascent without rocket assist. The orbiters would retain the SSME used on the USAF/Boeing Beta orbiter and would be designed at the initial thrust-to-weight determined to be optimum, except where this would require thrust levels higher than that available from the SSME (maximum vacuum thrust of 516,000 lb). When this occurred, the thrust of the SSME would be constrained to the maximum value and the initial thrust-to-weight of the orbiter allowed to vary.

The results from the analyses of the Beta-B1 and Beta-B2 vehicles, indicated in Figure 2, were studied to determine which direction the NASA Lewis TSTO study would follow next. As previously stated, one of the goals of the study was to develop a vehicle with a minimum gross takeoff weight subject to study guidelines and technology requirements. The Beta-B1 vehicle, staging at Mach 6.5, had a lower takeoff gross weight than Beta-B2, staging at Mach 4.5 and using only hydrocarbon fuel. The Beta-B1 vehicle was therefore chosen for further study.

At this juncture in the study, the opportunity was taken to modify and refine the Beta-B1 vehicle. First, the orbiter was changed from a lifting body to a more conventional wing-body configuration. The new orbiter configuration was proposed by Boeing and offered greater structural efficiency than the lifting body design but decreased cross-range capability. Large cross-range capability had been one of the requirements of the original USAF/Boeing Beta study. The NASA Lewis study, however, was more interested in developing a low weight vehicle than one with a large cross-range capability. Therefore, the orbiter configuration change was beneficial for this study. Growth margins were increased to 10 percent of the orbiter dry weight and 20 percent of the booster dry weight (ref. 1). These values were also suggested by Boeing and were more appropriate for the technology level assumed. Airbreathing propulsion (refs. 3,4) and vehicle aerodynamic data developed for the USAF/Boeing Beta vehicle were replaced by data developed at NASA Lewis for the Beta-B1 configuration. This included the substitution of turbojets currently being studied for high speed civil transports (HSCT) for the smaller ATF turbofan engines. Similar technology requirements between the HSCT and TSTO studies and decreased development costs due to parallel efforts were the elements considered in this decision. Finally, the volume and weight of the JP propellant required to return the booster from the staging point to the airfield and expended during takeoff were included in the analysis. Although included in the USAF/Boeing Beta study, the booster return fuel had not been considered in the Beta-B studies. Neither the USAF/Boeing Beta study nor the Beta-B studies had included takeoff fuel volume and weight. Though important in the final analysis, these were not considered to be major factors in the Beta-B decision process.

The final results of the study, after incorporating the modifications described above, appear in Figure 2. Details of the Beta II vehicle development are discussed in the following sections.

Analysis Tools and Methods

Four analysis codes were used to perform the mission and sizing studies for developing the Beta II vehicle. These were the Configuration Sizing program (CONSIZ), the Solid Modeling Aerospace Research Tool (SMART), the Optimal Trajectories by Implicit Simulation program (OTIS), and the Vehicle Integrated System Analysis program (VISA). The interaction between these analysis codes is depicted in Figure 3. Due to the complexity of the analysis procedure, the orbiter and booster were modeled and studied separately. A brief description of the codes and the analysis procedure appears below.

Orbiter sizing and weight analysis was performed with CONSIZ (ref. 5). CONSIZ provided a flexible method for calculating orbiter weight, scaling orbiter dimensions, and scaling the payload size for a fixed orbiter dry or gross weight. Weight estimating relations, orbiter dimensions, and orbiter packaging characteristics (i.e., tank efficiency, volume, etc.) were put into CONSIZ. The latter two of these inputs were generated by the SMART code (ref. 6). SMART is a general solid modeling program for the layout and geometric analysis of aerospace vehicles. Orbiter dimensions, volumes, and areas were calculated using SMART. In addition, changes in orbiter dimensions resulting from the analysis were put into SMART for visually checking sizing results.

CONSIZ was developed mainly for sizing rocket powered vehicles. Booster sizing was therefore performed with VISA, a tool which simulates the aerodynamic, weight, and trajectory performance for both rocket and airbreathing powered vehicles. VISA requires a nominal trajectory as input. Empirical weight models modified for the technology level assumed in this study were used within VISA to calculate weights and scale the vehicle based on the trajectory. As with the orbiter, changes in booster dimensions predicted by VISA were put into SMART for a visual check of the analysis results.

Trajectory optimization for both the orbiter and booster was performed with OTIS (ref. 7). OTIS is a program for simulating and optimizing point mass trajectories of various aerospace vehicles with provisions made for free and fixed end constraints, specified waypoints, and path constraints. For this study, OTIS was used to find optimal trajectories while satisfying maximum dynamic pressure, engine operation points, and staging Mach number constraints. Analysis of the orbiter occurred in the following manner. The initial vehicle definition was input to CONSIZ and SMART. Orbiter gross weight, calculated using CONSIZ, and initial gross thrust were transferred to OTIS and the trajectory analysis was performed. The resulting burnout weight was used to calculate the mass ratio (gross weight divided by burnout weight), which was then passed back to CONSIZ. Iterations were performed until the gross weight converged. Analysis of the booster was accomplished using OTIS to determine the optimum trajectory and VISA to scale the initial vehicle accordingly based on this trajectory. Iterations between OTIS and VISA were performed until the vehicle could complete the mission within the guidelines of the given propulsion system, aerodynamics, and mission constraints. Initial trade studies were performed with OTIS and VISA in a similar manner.

Airbreathing propulsion data was calculated in-house at NASA Lewis using the NASA Engine Performance Program, (NEPP, previously known as NNEP89, ref. 8) for the prediction of the HSCT turbojet performance and RAMSCRAM (ref. 9) for the prediction of ramjet performance. Vehicle aerodynamic data were calculated in-house using the Aerodynamic Preliminary Analysis System (ref. 10). The results of these analyses were incorporated into the mission studies during the refinement of the Beta-B1 vehicle to produce Beta II.

Initial Trade Studies

The mission and sizing analysis of the TSTO vehicle began with two sets of studies. First, the optimum initial thrust-to-weight for the orbiter was determined. The second set of initial studies, performed on the booster, included investigating the effects of changing the staging Mach number and decreasing the orbiter payload on the booster propulsion system. In addition, the propulsion system mix (ratio of turbofan to ramjet thrust) on the booster was optimized for an all airbreathing ascent to staging. The results of these studies were used in the development of the Beta-B and Beta II vehicles. This discussion presents the assumptions and results of these initial studies.

Orbiter Thrust-To-Weight Optimization

As discussed above, one of the study goals was to develop a TSTO vehicle optimized for minimum takeoff gross weight. Designing the orbiter for optimum staging thrust-to-weight would help obtain this goal. Therefore, a study was conducted to determine the optimum T/W for an orbiter similar to the USAF/Boeing Beta configuration but carrying a 10,000 lb payload. The optimum orbiter trajectory found with OTIS was used in VISA. The T/W ratio of the orbiter was varied and the orbiter gross weight determined. The results of this study are shown in Figure 4. It should be noted that the graph in Figure 4 is normalized with the optimum point corresponding to a relative gross weight of unity and an initial T/W ratio of 1.17. As discussed previously, the rocket engine thrust and weight were scaled for each orbiter T/W such that the rocket operated at maximum thrust at staging. This thrust level was then maintained throughout the trajectory. This analysis was repeated for various staging Mach numbers; all produced an initial T/W of approximately 1.17. Orbiter design at this optimum initial T/W occurred in subsequent analyses except where the required thrust exceeded the limitations of the SSME. In this case, the orbiter thrust-to-weight was allowed to vary.

Booster Propulsion System Optimization Analysis

The next set of trade studies investigated the effects of modifying the USAF/Boeing Beta vehicle to meet the NASA Lewis study goals on the booster propulsion system. These modifications included decreasing the staging Mach number, eliminating the rocket system from the booster, and decreasing the orbiter payload weight. The remaining airbreathing propulsion system mix (ratio of turbofan to ramjet thrust) was then optimized to perform the initial ascent without rocket assist for a minimum takeoff gross weight vehicle.

The first modification made to the USAF/Boeing Beta vehicle (represented by the first bar in Figure 5) was the reduction of the staging Mach number from 8 to 6.5. Mach 6.5 was judged as the feasible limit for the hydrogen fueled ramjets at the technology level assumed in the NASA Lewis TSTO study. As the staging Mach number decreased, orbiter weight and size increased since it now performed a larger part of the mission. The physical size of the booster and, therefore, the booster structural weight, increased to accommodate the larger orbiter. The takeoff gross weight (TOGW) of this vehicle (represented by the second bar in Figure 5) was therefore larger than that of the original USAF/Boeing vehicle.

The next step in the study involved determining if rocket propulsion was necessary during the boost phase of the mission. The rocket propulsion provided an Isp of 460 sec, much lower than the ramjet Isp of approximately 4000 sec. Therefore, eliminating the rocket propulsion would potentially reduce the overall weight of the vehicle. The size of the airbreathing propulsion systems would need to be increased, however, to provide the thrust required to accelerate through the transonic region. As shown in the third bar in Figure 5, removing the rocket from the booster did result in a large reduction in TOGW over the configurations with rocket propulsion. This reduction resulted from a decrease in the propellant required for the booster. Employing only airbreathing propulsion systems for the initial ascent eliminated the need for liquid oxygen in the booster and reduced the necessary amount of liquid hydrogen in the booster by half.

The effect of reducing the orbiter payload capability from 50,000 to 10,000 lb was then studied. As shown in the fourth bar in Figure 5, this resulted in a large decrease in both the orbiter weight and in the overall vehicle TOGW. However, this reduction was not in proportion to the payload weight reduction. This was a result of the non-linear relation between payload weight and vehicle structural weight.

Finally, the staging Mach number was reduced from 6.5 to 4.5 and the LH2 fuel used in the ramjet was replaced with JP-7 fuel. This produced an effect similar to that of the first Mach number reduction from 8.0 to 6.5. The TOGW of the vehicle increased due to the heavier orbiter and the reduced Isp of the JP fueled ramjets. This effect is shown in the last bar of Figure 5.

The results of the trade study indicated that the elimination of rocket propulsion during the initial ascent was beneficial in reducing the TOGW. However, as previously discussed, the rocket propulsion provided a large percentage of the thrust during the boost phase of the USAF/Boeing Beta vehicle. To compensate for this loss, the thrust produced by the airbreathing propulsion systems was increased and optimized to produce a minimum TOGW vehicle. This was accomplished by sizing the turbofan and ramjet thrusts independently of one another. A family of vehicle takeoff thrust-to-weight versus TOGW curves was produced for varying combinations of turbofan and ramjet thrust levels. An example of this is shown in Figure 6. Each curve produced an optimum vehicle T/W ratio, which corresponded to a minimum TOGW and ratio of turbofan takeoff thrust to maximum ramjet thrust. The locus of the optimum points in Figure 6 are shown in Figures 7 and 8. Figure 7 indicates the optimum vehicle T/W ratio was 0.55. Figure 8 shows the optimum turbofan to ramjet thrust ratio to be approximately 0.60. The results of this study were used as a guide to size the booster airbreathing propulsion system for the Beta-B1, Beta-B2, and Beta II configurations.

Beta-B Vehicle Development

Following the initial trade studies, two TSTO vehicle concepts were identified for analysis. Both vehicle configurations were derived from the USAF/Boeing Beta study vehicle. Both would be designed to deliver and return a 10,000 lb payload to low Earth polar orbit. Finally, both vehicles would be designed to perform the initial ascent utilizing only airbreathing propulsion. These vehicles were termed Beta-B1 and Beta-B2. Beta-B1 staged at Mach 6.5; Beta-B2 staged at Mach 4.5. The goal of the study continued to be the development of a vehicle with minimum takeoff gross weight utilizing 1995 technology.

Vehicle Trajectory

The ascent trajectories for the Beta-B1 and Beta-B2 vehicles appear in Figure 9. The two trajectories were very similar: the dynamic pressure was constrained to a maximum of 1500 lb/ft^2, the ramjets began producing thrust at Mach 1, the turbomachinery operated up to Mach 3 and, unlike the USAF/Boeing Beta vehicle trajectory, the orbiter SSME did not fire until staging. Both the Beta-B1 and Beta-B2 vehicles executed a dive near the transonic region, trading potential energy for kinetic energy to overcome the high transonic drag of the vehicle. Both trajectories also show a period of orbiter acceleration at slightly decreasing altitude directly following staging before a traditional rocket trajectory was followed. This was a result of the orbiter lifting body configuration; when optimizing the orbiter trajectory, OTIS took advantage of the lift-to-drag ratio of the orbiter (approximately 3) to accelerate the orbiter in the atmosphere. The Beta-B1 and Beta-B2 trajectories differed at the staging point. For the Beta-B1 vehicle, staging occurred at Mach 6.5 and at an altitude of 100,000 ft. The Beta-B2 staged at Mach 4.5 and 87,000 ft. The altitude at staging was decreased for the Beta-B2 vehicle to produce a staging dynamic pressure of 700 lb/ft^2. This pressure was consistent with that of the Beta-B1 orbiter and was high enough to assure sufficient ramjet performance at the staging point.

Orbiter Analysis and Results

The Beta-B1 and Beta-B2 orbiters were developed to perform the design mission with a minimum gross weight. A payload bay volume of 3000 ft^3 was assumed and held constant while scaling the vehicle. An additional 400 ft^3 was held constant to account for crew compartment volume. The weights of the SSME and its associated systems were held constant as the vehicle was sized, as were personnel and personnel system weights. As discussed above, a small growth margin equal to two percent of the orbiter dry weight was included in the weight of each orbiter. This value was used in the original USAF/Boeing vehicle definition and was retained during this part of the NASA Lewis analysis. The initial thrust-to-weight of the Beta-B1 orbiter was fixed at the optimum value of 1.17 by throttling the SSME. For the Beta-B2 orbiter, however, the thrust required to obtain a T/W value of 1.17 was greater than the thrust available from the SSME. Therefore, the thrust of the SSME on the Beta-B2 orbiter was constrained to a maximum value of 516,000 lb and the thrust-to-weight was allowed to vary. The resulting staging T/W for the Beta-B2 orbiter was 1.04. The thrust level of the SSME was held constant for both orbiters throughout the trajectory.

The gross weights of the orbiters are shown in Figure 10 with that of the original Beta orbiter. As expected, the decrease in payload weight led to a large decrease in the gross weight of the orbiter. Staging at Mach 6.5 produced the lightest orbiter (Beta-B1) with a gross weight of approximately 359,000 lb. The Beta-B2 orbiter was heavier with a gross weight of 498,000 lb. This was due to the increased fuel requirements at the lower staging Mach number and to the inability to operate at the optimum thrust-to-weight ratio. The Beta-B1 and Beta-B2 results are represented by the second and third bars in Figure 10, respectively. As shown in the figure, the fuel required for ascent from staging to orbit constitutes a large part of the orbiter gross weight for all three vehicles.

Booster Analysis and Results

The Beta-B1 and Beta-B2 boosters were designed for minimum takeoff gross weight to transport the respective orbiters to staging. The orbiter volumes were treated as fixed payload volumes for the boosters. Personnel and personnel systems weights were held constant as was the orbiter weight. A growth margin equal to 2.5 percent of the booster dry weight was included in the booster weight definition, as discussed above. Similar to the orbiter growth margin, this low value was retained from the original USAF/Boeing Beta vehicle definition. This part of the NASA Lewis study was conducted with the propulsion and aerodynamic data developed for the USAF/Boeing Beta vehicle (ref. 1). The fuel burned by the vehicle during takeoff, and that needed to return the booster from the staging Mach number and altitude to the airfield, were not included in the analysis of the Beta-B boosters. These were not considered major factors in this part of the NASA study. The ramjets on the Beta-B1 booster were fueled with LH2. Those on the Beta-B2 booster utilized JP fuel.

Gross weights for the Beta-B1 and Beta-B2 boosters, which include the orbiter weights as booster payload, are presented in Figure 11 with that of the USAF/Boeing Beta booster. The decrease in orbiter payload weight again resulted in vehicles with gross weights much lower than that of the USAF/Boeing Beta. Staging at Mach 6.5 produced the Beta-B1 booster with a gross weight of approximately 641,000 lb. The Beta-B2 booster, staging at Mach 4.5, was heavier with a gross weight of approximately 927,000 lb. The increased weight of the Beta-B2 orbiter over that of the Beta-B1 orbiter caused the Beta-B2 booster structural weight to increase. The Beta-B1 and Beta-B2 booster gross weights are represented by the second and third bars in Figure 11, respectively.

At this point in the study, a decision was made to determine which vehicle, Beta-B1 or Beta-B2, would undergo further development. The goal of developing a vehicle with a reasonable takeoff gross weight would be best achieved by choosing the lower weight Beta-B vehicle. This would allow for weight growth which could occur as the vehicle was refined. The hydrogen fueled Beta-B1 vehicle, staging at Mach 6.5 with a TOGW of 641,000 lb, was therefore chosen for further study and refinement into the Beta II baseline TSTO vehicle.

Beta II Vehicle Development

The final NASA Lewis TSTO vehicle, Beta II, evolved from the Beta-B1 vehicle. This evolution included: a change in the orbiter configuration, the increase of both the orbiter and booster growth margins, the replacement of both the USAF/Boeing Beta aerodynamic and airbreathing propulsion data with in-house results, and the inclusion of takeoff and booster return fuel.

Beta II Configuration

The final Beta II configuration appears in Figure 12. Although Beta II is very similar to the original USAF/Boeing Beta configuration, it incorporates many different design features. Due to the elimination of both the booster rocket and the necessity for transferring propellant to the orbiter rocket, no oxidizer is required on the booster. As discussed above, the Beta II orbiter is a wing-body design, unlike the lifting body orbiter found in the USAF/Boeing vehicle. The Beta II orbiter has a cylindrical body that, while decreasing the cross-range capability of the orbiter, gives greater structural efficiency than the lifting body design. In addition, the Beta II orbiter is easier to "package" into the booster because of its slimmer, cylindrical shape. Figure 12 shows that the orbiter includes a folding canard in the forward part of the body. This is necessary for control during landing (ref. 1).

Vehicle Trajectory

The trajectory for the Beta II vehicle appears in Figure 9. It is similar to that for the Beta-B1 orbiter. However, the wing-body configuration had a lower lift-to-drag ratio (approximately 2.1) than the Beta-B1 lifting body orbiter. The orbiter trajectory therefore followed a traditional rocket trajectory directly following staging. A three-G acceleration limit was imposed on the Beta II orbiter after staging. Upon reaching that limit, the SSME was throttled to maintain a constant three-G acceleration until orbital insertion.

Beta II Orbiter Analysis and Results

The Beta II orbiter was optimized to perform the design mission with a minimum gross weight. The payload volume, 3000 ft^3, remained constant. Volumes and weights held fixed for the Beta-B1 orbiter analysis were likewise fixed. A significant change in the Beta II orbiter analysis was the increase of the growth margin from 2 to 10 percent of the orbiter dry weight. This value was suggested by Boeing as more appropriate for this vehicle type and the technology level assumed. The staging thrust-to-weight of the Beta II orbiter was fixed at 1.17 and the SSME thrust held constant, similar to the Beta-B1 orbiter, except where the three-G limit was imposed.

A comparison of the Beta II orbiter gross weight with the Beta-B1 orbiter weight is shown in Figure 10 (fourth and second bars, respectively). As can be seen, the two orbiter gross weights were nearly identical. The weight increase that resulted from the larger growth margin for the Beta II orbiter was offset by the greater structural efficiency of the wing-body design. The Beta II orbiter completed the mission with a gross weight of approximately 359,000 lb, similar to the Beta-B1 orbiter.

Beta II Booster Analysis and Results

The Beta II booster was designed for minimum takeoff gross weight to carry the Beta II orbiter to an altitude of 100,000 ft and a staging Mach number of 6.5. Similar to both Beta-B vehicles, the orbiter volume and weight were treated as payload and were fixed. The propulsion system on the Beta II booster was similar to that of the Beta-B1; however, the ATF turbofans from the USAF/Boeing Beta booster were replaced with larger turbojets (60,000 lb thrust) currently being studied for high speed civil transports. The appropriate propulsion data was used in the analysis. Aerodynamic results calculated at NASA Lewis for the Beta-B1 configuration were used in this part of the analysis in place of the USAF/Boeing Beta results. The growth margin for the Beta II booster was increased from the original value of 2.5 to 20 percent of its dry weight. Similar to the orbiter growth margin, this value was determined to be much more realistic for the complexity assumed in this study. Estimates of the fuel expended during takeoff and that needed for returning the booster from the staging point to the airfield were found with OTIS and VISA and were included in this part of the study.

A comparison of the Beta II and Beta-B1 booster weights (including the orbiter weights as booster payloads) is shown in Figure 11 (fourth and second bars, respectively). As can be seen, the takeoff gross weight of the Beta II booster is almost twice that of the Beta-B1 booster. This large increase resulted in part from the increased growth margin discussed above. The application of refined aerodynamic results to the study also led to an increase in the booster gross weight. The Beta II booster body (Figure 12) had a greater fineness ratio than the USAF/Boeing Beta booster; the width of the Beta II booster nacelles, however, did not decrease from that of the Beta nacelles in the same proportion. The area ruling of the Beta II booster was thus less ideal than that of the USAF/Boeing booster, resulting in greater transonic drag and an increase in gross weight. Finally, the addition of takeoff and booster return fuel led to a further increase in the Beta II booster gross weight above that of the Beta-B1 booster.

In spite of these weight increases, the Beta II vehicle was able to complete the design mission of delivering and returning a 10,000 lb payload to low Earth polar orbit with a gross weight of approximately 1.1 Mlb utilizing only airbreathing propulsion for the initial ascent. Thus, the Beta II vehicle satisfies the study goals and requirements.

Payload Capability to Space Station Orbit

The design mission to low Earth polar orbit (100 n. mi.) was chosen to maintain continuity with other similar studies. However, the ability of the TSTO system to deliver payload to the Space Station (28.5 degree inclination, 180 n. mi. circular orbit) and possibly to a low circular equatorial orbit (100 n. mi.), is also of interest for many future NASA missions. Examples of these are Space Station resupply or rescue missions and satellite servicing. In addition, the ability of the orbiter to carry payload when forced to stage at a Mach number lower than its design value was of interest. This would enable vehicle operation even if the airbreathing propulsion systems on the booster were not able to meet their predicted high speed performance level in the near term. The payload carrying capability of the Beta-B1 orbiter, designed for Mach 6.5 staging, was investigated for three orbits— polar, Space Station, and equatorial—for staging Mach numbers ranging from 4.5 to 6.5. At the time this study was implemented, definition of the Beta II vehicle had not been completed. However, it was judged that the results obtained for the lifting body Beta-B1 orbiter could be extended to the Beta II wing-body orbiter.

This analysis was performed with the assumption that the orbiter dry weight and gross weight remained constant. Thus, neither orbiter nor booster redesign was considered allowable. The effect of staging at different Mach numbers or to different orbits on the booster gross weight was not studied. It was assumed that the orbiter would be staged in the proper position to obtain its orbit efficiently. OTIS was used to determine the fuel required for the orbiter to reach each orbit when staging from various Mach numbers. CONSIZ was then employed to determine the change in payload weight that resulted from the differing fuel requirements.

The results of this study are shown in Figure 13. The dotted line indicates the point at which redesign of the orbiter internal packing, i.e., resizing of the fuel tanks and payload bay, would be required to fulfill the mission. For payloads above the dotted line, no repackaging would be necessary. For those below the dotted line, resizing of the fuel tanks and payload bay and repackaging would be necessary to complete the mission. As can be seen, performing the design mission to low Earth polar orbit when staging at a Mach number below 6.5 would require repackaging of the orbiter. This result was expected, since the Beta-B1 orbiter was designed for staging at Mach 6.5. The maximum payload capability of the orbiter ascending to a nominal Space Station orbit is approximately 17,500 lb when staging at Mach 6.5. A 20,000 lb payload could be delivered to a low equatorial orbit at the same staging Mach number.

Future Refinements

The Beta II vehicle was developed as a baseline vehicle for further NASA Lewis TSTO studies. These include: a more detailed analysis of the Beta II aerodynamic characteristics, particularly in the transonic region; a detailed structural and thermal analysis of the booster airbreathing propulsion system; an investigation of the optimum staging Mach number; an analysis of the takeoff and landing field requirements, and a cost analysis. In addition, study of a non-cryogenic TSTO vehicle similar to Beta II is planned (ref. 2).

Summary

NASA Lewis Research Center investigated a TSTO vehicle called Beta II. Beta II was derived from the USAF/Boeing Beta study vehicle, also a TSTO system. In accordance with study guidelines, Beta II was developed using near-term (i.e., 1995) technology to deliver and return a 10,000 lb payload to low Earth polar orbit. In addition, it was determined that the boost phase of the mission, from takeoff to Mach 6.5 and 100,000 ft, could be completed using only airbreathing propulsion systems. Beta II was shown to be capable of completing the design mission while meeting study requirements and goals with a minimum takeoff gross weight of approximately 1.1 Mlb. This result, slightly greater than large commercial transports, was judged to be reasonable for this vehicle type. The optimum initial thrust-to-weight of the Beta II orbiter was found to be 1.17; the minimum gross weight of the Beta II orbiter at this T/W was shown to be approximately 359,000 lb. In addition to completing its baseline mission, the Beta II vehicle was shown to be capable of delivering approximately 17,500 lb to the Space Station.

The Beta II TSTO vehicle provides a baseline for future NASA Lewis studies. Further investigation of the Beta II characteristics will lead to a better defined vehicle as well as provide information which can be used in similar TSTO studies.

References

1. Paris, S.W.; Wetzel, E.D.; Meadowcroft, E.T.; Weldon, V.A.; Kotker, D.J.; Williams, D.P.; Dunn, B.M.; Twitchell, S.; Vlases, W.G.: Research Vehicle Configurations for Hypervelocity Vehicle Technology. WRDC-TR-90-3003, Volumes I and II, Apr. 1990, Volume IIA, July 1991.

2. Plencner, R.M.: Overview of the Beta II Two-Stage-to-Orbit Vehicle Design. AIAA Paper 91-3175, Sept. 1991.

3. Snyder, C.A.; Maldonado, J.J.: The Design and Performance Estimates for the Propulsion Modules for the Booster of a TSTO Vehicle. AIAA Paper 91-3136, Sept. 1991.

4. Midea, A.C.: Mach 6.5 Air Induction System Design for the Beta II Two-Stage-to-Orbit Booster Vehicle. AIAA Paper 91-3196, Sept. 1991.

5. Lepsch, R.A.; Stanley, D.O.; Cruz, C.I.; Morris, Jr., S.J.: Utilizing Air-Turborocket and Rocket Propulsion for a Single-Stage-to-Orbit Vehicle. AIAA Paper 90-0295.

6. McMillan, M.L.; Rehder, J.J.; Wilhite, A.W.; Schwing, J.L.; Spangler, J.; Mills, J.C.: A Solid Modeler for Aerospace Vehicle Design. AIAA Paper 87-2901, Sept. 1987.

7. Vlases, W.G.; Paris, S.W.; Lajoie, R.M.; Martens, P.J.; Hargraves, C.R.: Optimal Trajectories By Implicit Simulation Version 2.0. WRDC-TR-90-3056, Dec. 1990.

8. Plencner, R.M.; Snyder, C.A.: The Navy/NASA Engine Program (NNEP89)—A User's Manual. NASA TM-105186, 1991.

9. Burkardt, L.A.; Franciscus, L.C.: RAMSCRAM—A Flexible Ramjet/Scramjet Engine Simulation Program. NASA TM-102451, 1990.

10. Bonner, E.; Clever, W.; Dunn, K.; Divan, P.; Sova, G.: Aerodynamic Preliminary Analysis System II, Parts I and II. NASA CR-182076, 182077, Apr. 1991.

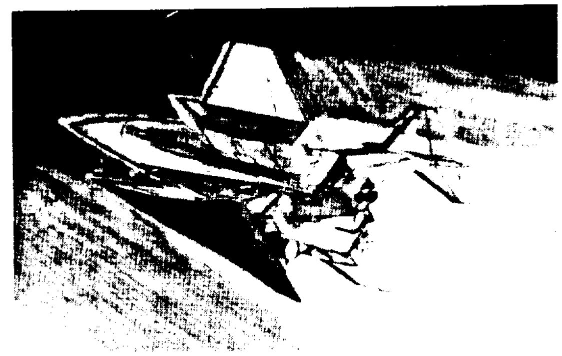


Figure 1. USAF/Boeing Two-Stage Beta Vehicle.

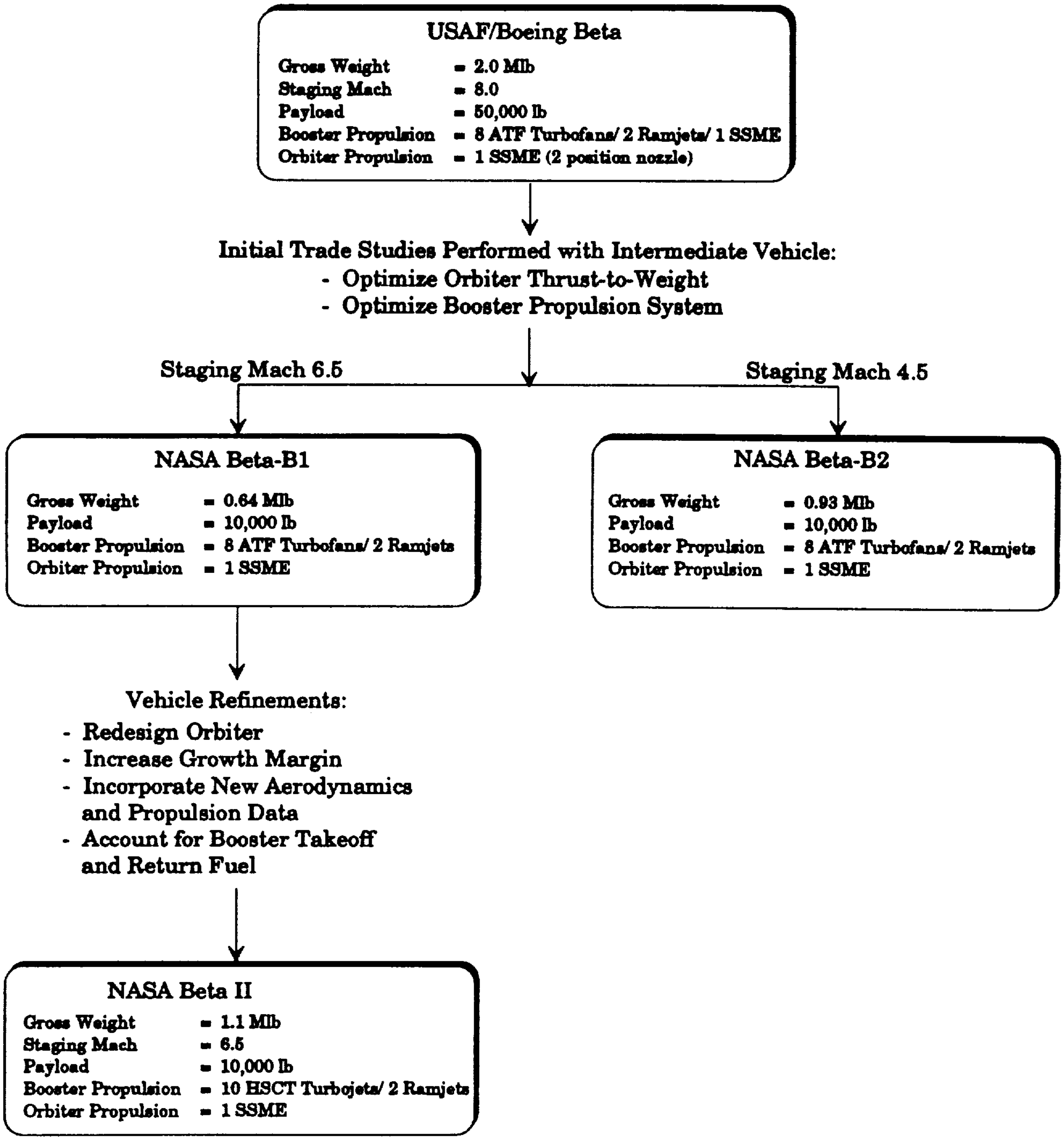


Figure 2. Progression from USAF / Boeing Beta to NASA Lewis Beta II.

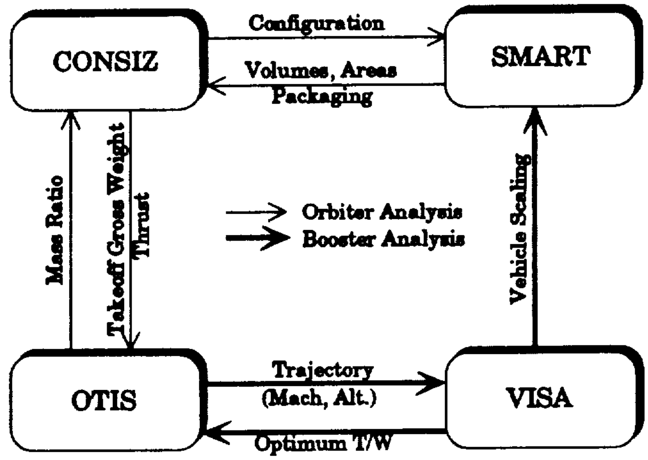


Figure 3. Data Flow Between Analysis Programs.

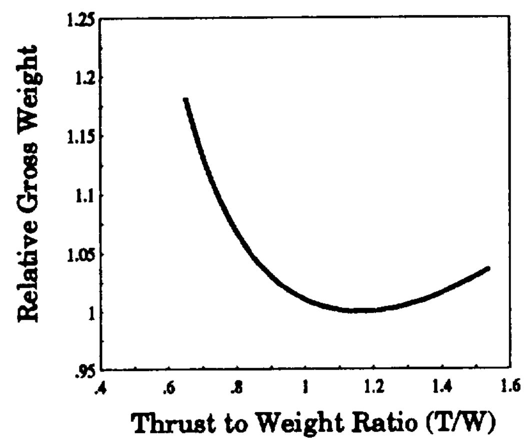
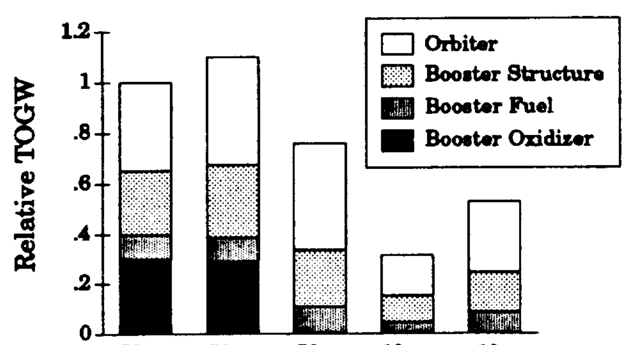


Figure 4. Gross Weight of an Orbiter With Varying Staging Thrust-to-Weight Ratio.



Payload (klb)	50	50	50	10	10
Stage Mach	8.0	6.5	6.5	6.5	4.5
Airbreathing T/W	.144	.154	.525	.570	.605
Boost Rocket T/W	.472	.504	0	0	0
Boost Propellants	$JP/H_2/O_2$	$JP/H_2/O_2$	JP/H_2	JP/H_2	JP

Figure 5. TOGW for Various Booster Propulsion System Configurations.

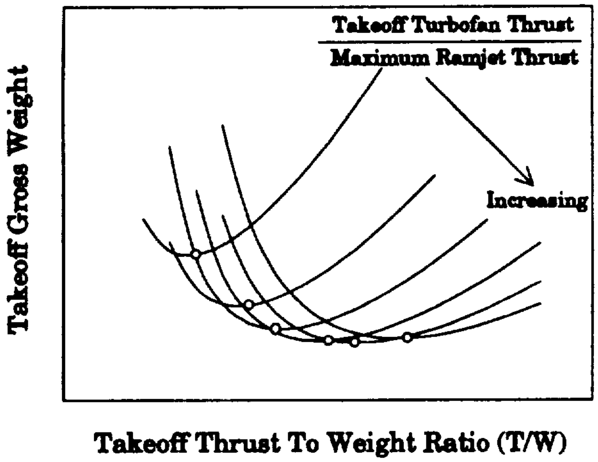


Figure 6. Optimal Booster T / W and Turbojet to Ramjet Thrust Ratio.

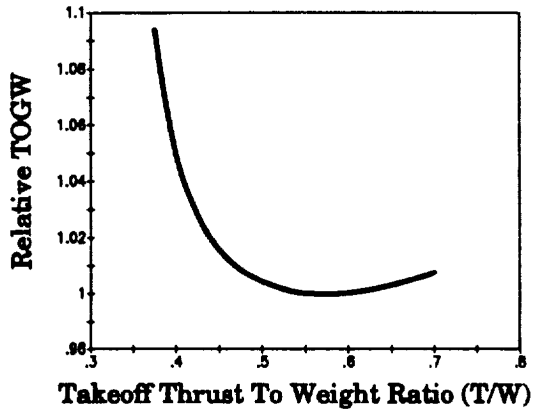


Figure 7. Relative TOGW for Booster With Varying Thrust-to-Weight Ratio.

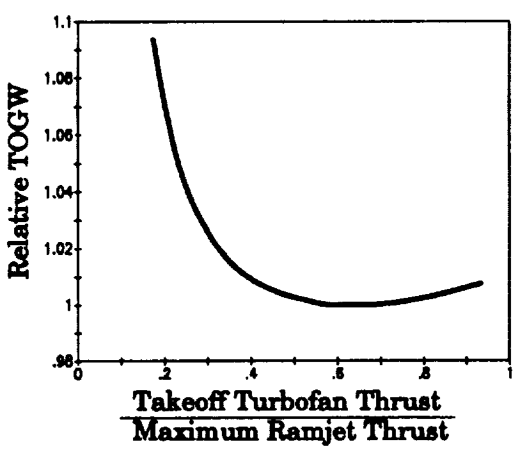


Figure 8. Relative TOGW for Booster With Varying Turbofan / Ramjet Thrust Ratio.

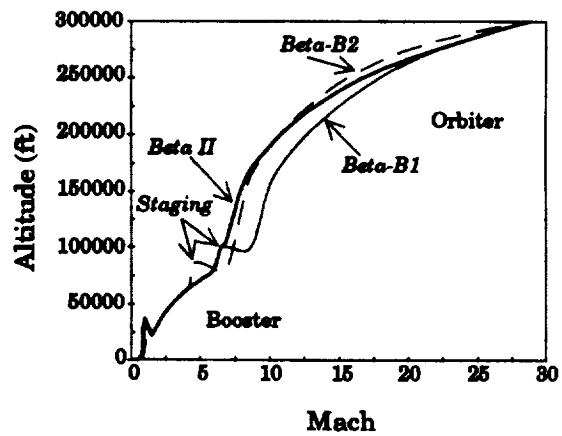


Figure 9. NASA Lewis Beta Trajectories.

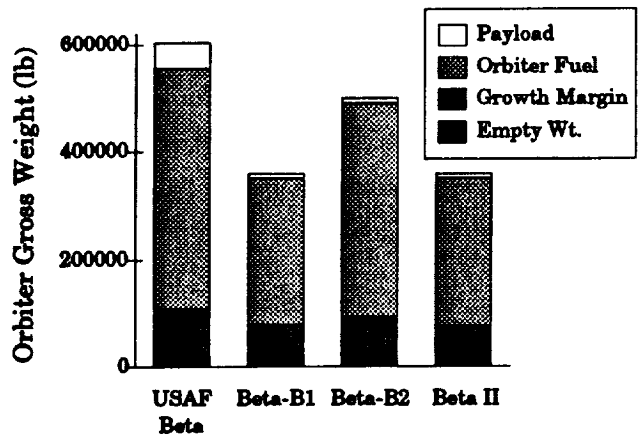


Figure 10. Gross Weight of NASA Lewis Orbiters.

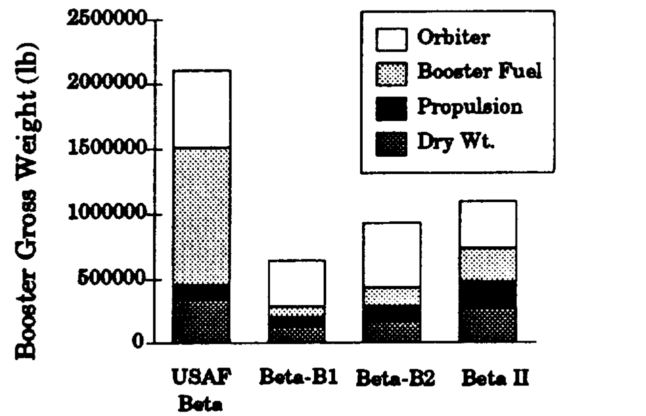


Figure 11. Gross Weight of NASA Lewis Boosters.

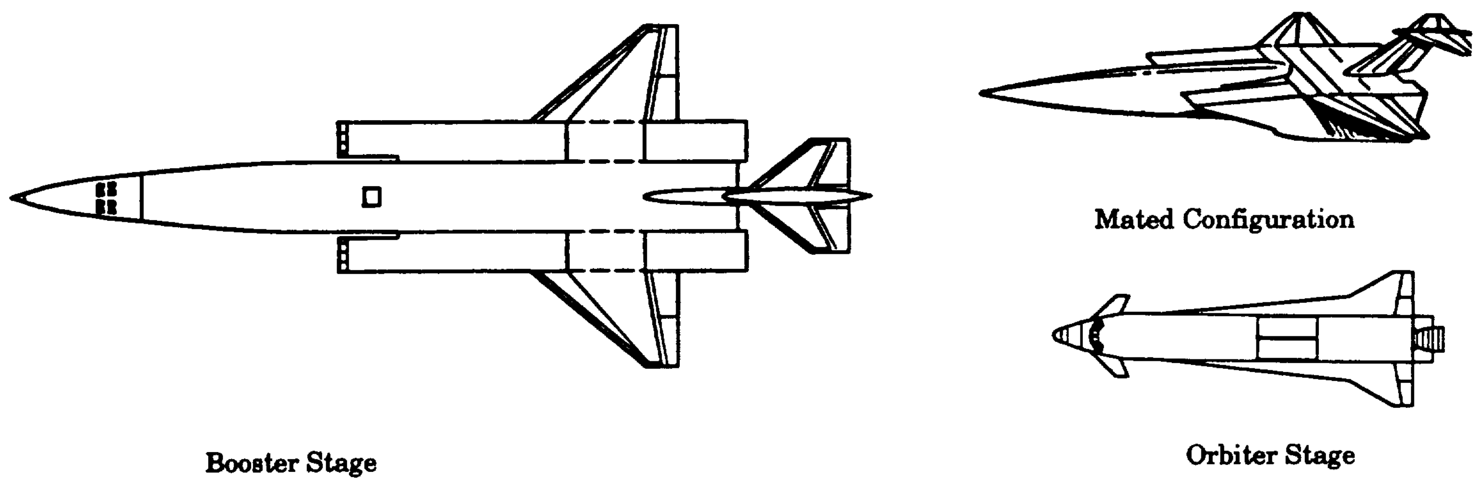


Figure 12. NASA Lewis Beta II General Layout.

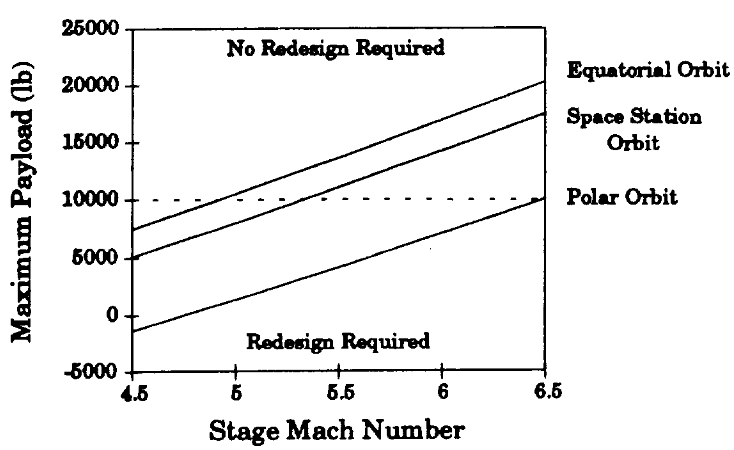


Figure 13. Beta-B1 Orbiter Payload Capability for Various Orbits.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1992

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Mission and Sizing Analysis for the Beta II Two-Stage-to-Orbit Vehicle

5. FUNDING NUMBERS
WU-505-69-40

6. AUTHOR(S)
Shari-Beth Nadell, William J. Baumgarten, and Stephen W. Alexander

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-6883

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-105559
Corrected Copy

11. SUPPLEMENTARY NOTES
Prepared for the 1992 Aerospace Design Conference sponsored by the American Institute of Aeronautics and Astronautics, Inc., Irvine, California, February 3-6, 1992. Responsible person, Shari-Beth Nadell, (216) 977-7035.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories 15 and 5

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

NASA Lewis Research Center studied a horizontal takeoff and landing, fully reusuable, two-stage-to-orbit (TSTO) vehicle capable of launching and returning a 10,000 pound payload to low Earth polar orbit using low-risk technology. The vehicle, called Beta II, was derived from the USAF/Boeing Beta vehicle, a TSTO study vehicle capable of launching a 50,000 pound payload to low Earth polar orbit. Development of Beta II from the USAF/Boeing Beta vehicle occurred in a series of iterations during which the size of the vehicle was decreased to accommodate the smaller payload, the staging Mach number was decreased from 8.0 to 6.5, and the rocket propulsion system was removed from the booster. The final Beta II vehicle consisted of a rocket powered orbiter and an all airbreathing booster. The gross takeoff weight of the Beta II vehicle was approximately 1.1 million pounds. In addition to its baseline mission, the Beta II vehicle was capable of delivering approximately 17,500 lb to the Space Station with the same takeoff gross weight. The mission and sizing analysis performed to arrive at the Beta II vehicle is discussed.

14. SUBJECT TERMS
Aircraft design; Airbreathing boosters; Reusable launch vehicles; Hypersonic aircraft

15. NUMBER OF PAGES
16

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

National Aeronautics and
Space Administration

Lewis Research Center
Cleveland, Ohio 44135